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(NASA-CR-170018) A SELF-CONSISTENT COMPUTER
CODE FOR PARTICLE SIMULATIONS Final Report,
1 Oct. 1980 - 30 Sep. 1981 (Stanford Univ.)
21 p HC A02/MF A01

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FINAL REPORT
on work carried out under
NASA GRANT NAG5-120



March 1983

I. Grant Purpose

The purpose of this Grant (NAG5-120) was to support a Guest Investigator study involving computer simulations of VLF wave-particle interactions observed in the magnetosphere from the ISEE-1 spacecraft.

II. Period of Performance

The period of performance under this contract extended from October 1, 1980, to September 30, 1981.

III. Work Provided

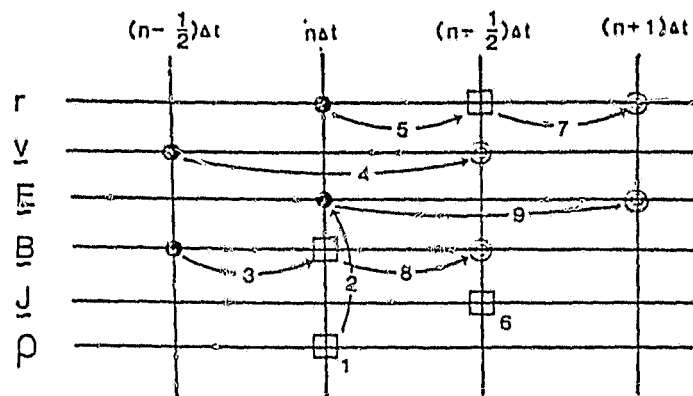
The purpose of the present study was to develop a self-consistent computer code for particle simulations which could treat both Landau and cyclotron interactions. The main part of a two-and-one-half dimensional (2-1/2D) electromagnetic (EM) simulation code (referred to as the 'EM2 code' hereafter) was programmed during the time spent by Dr. H. Matsumoto as a Guest Investigator at Stanford University. The code treats the two-dimensional field structure as well as the three-dimensional particle motion that are involved in interactions between obliquely propagating VLF waves and energetic electrons in the magnetosphere.

Figure 1 shows a sequence of operations in one time-step in the EM2 code where Δt is an increment of the time-step and n is an integer showing the step number. Four solid circles in the upper panel indicate the initial values given at the n^{th} time-step. Step 1 calculates the number density ρ on all grids by a scheme of area sharing of super-particles with a shape of rectangular charge. In Step 2, we compute an electrostatic component of the electric field by solving the Poisson equation. An FFT technique is used in this calculation. In Step 3, we advance the magnetic field \bar{B} for a half time-step by a difference equation corresponding to

$$\frac{\partial \bar{B}}{\partial t} = -\nabla \times \bar{E} \quad (1)$$

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(EM2 Code)



Step 1 Form ρ

Step 2 Correct the Poisson Field

Step 3 Advance B

Step 4 Advance v by Buneman-Boris Method

Step 5 Advance r

Step 6 Form J

Step 7 Advance r

Step 8 Advance B

Step 9 Advance E

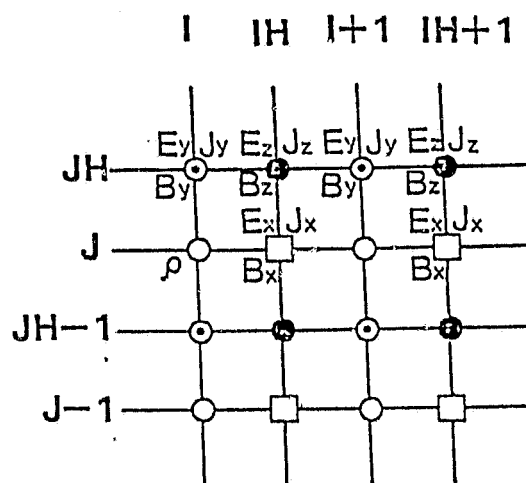
Figure 1. Leap-frog scheme and sequence of operations in one time-step in the EM2 Code.

Since the magnetic and electric fields are updated to this time, the equation of motion of particles can now be solved in Step 4. We use a Buneman-Boris scheme for the updating of the particle velocity \bar{v} . Then we advance particle position \bar{r} for the next half time-step in Step 5. As the particle velocities and positions are known, we next compute a current density \bar{J} on each grid point by distributing a quantity $q\bar{v}$ of each superparticle to the nearest four grid points by the area sharing scheme. In Step 7, the particle locations are updated. The magnetic field is then updated for the latter half time-step in Step 8. The electric field is finally updated in Step 9 by a difference equation corresponding to

$$\frac{\partial \bar{E}}{\partial t} = c^2 (\nabla \times \bar{B} - \mu_0 \bar{J}) \quad (2)$$

The correction of the electric field in the Poisson solver in Step 2 is necessary and mandatory to compensate for the short-term violation of the equation of continuity during the leap-frog scheme for the particle position \bar{r} and velocity \bar{v} . All difference equations for both the Maxwell equations and equation of motion are written in a time- and space-centered difference scheme which is time-reversible and of higher accuracy than forward or backward difference schemes. Figure 2 shows a staggered structure of the spatial grid points with full and half integer points on which the field, current, and charge quantities are assigned as indicated. This assignment and staggered leap-frog time scheme shown in Figure 2 are needed to construct the centered difference

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□ X point

⊙ Y point

⊙ Z point

○ C point

Figure 2. Staggered grid system used in the EM2 Code.

scheme for all equations, both in space and in time. Figure 3 shows the main program of the EM2 code.

The remaining subroutines and necessary diagnostic routines of the EM2 code were developed in Japan. The complete EM2 code requires more than 5,000 program statements. A detailed description of the code will be contained in a book entitled *Computer Simulations in Space Physics* (edited by H. Matsumoto and T. Sato), which will be published from Terra-Pub/D. Reidel Book Publishing Company this autumn or next winter.

In this report, we will present the results of two test runs of the EM2 code which demonstrate the validity of the code. One test run is designed to reproduce the dispersion characteristics of the normal modes of plasma waves in a homogeneous magnetized plasma. The other is designed to reproduce the propagation characteristics of a monochromatic wave of a known mode. Figure 4 shows the result of the first test and Figure 5 gives those of the second test. Figure 4-1 shows the dispersion of the measured wave fields after the test run, assuming an initial bi-Maxwellian velocity with a temperature anisotropy of $T_{\perp}/T_{\parallel} = 2$. The plasma frequency Π_e is set equal to 2 and cyclotron frequency Ω_e is set equal to 1. All modes predicted by the linear theory of plasma waves are seen in the results. Figure 4-2 illustrates the configuration of wave magnetic and electric-field vectors as well as of the wave number vector k for both O- and X-mode waves in a homogeneous magnetized plasma. Figure 4-3 and 4-4 show the results of the dispersion characteristics (analyzed by an FFT technique) of the O- and X-mode waves, respectively.

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MAIN PROGRAM FOR WHISTLER INTERACTION BY 2-D EM CODE

PROGRAMMED BY H. MATSUMOTO

JULY 1980

```

1  COMMON/INPCOM/IDIAG,NSTEP,NOBNUM,ION
2  COMMON/TIMECM/T
3  COMMON/CONSTC/P, C, DX, DY, DT, NX, NY, NP, QS, DKX, DKY, AMI,
    NX1, NY1, NPC, DX1, DY1, SLX, SLY, PDT, ANPCI,
    P2DT, PDT2, PDTDX2, PDTDY2, PC2DTX, PC2DTY,
    QMEDT, QMIDT, NX2, NY2

    DATA INPUT
    START
4      CALL INPUT
    INITIALIZATION
5      CALL INITIAL
    MAIN LOOP
6      DO 1000 I=1,NSTEP
    TIME
7      T = (I-1+NSTEP+JOBNUM)*DT
    JUDGE
8      J = MOD(I,IDIAG) - 1
9      IF(J.NE.0) GO TO 100
    DIAGNOSTICS
10     CALL DIAGNS
    B(N) TO B(N+0.5)
11     CALL BFIELD
    CORRECTION OF E
12     CALL ECRRCT
    B(N-0.5) TO B(N)
13     CALL BFIELD
    V(N-0.5) TO V(N+0.5)
14     CALL VELCTY
    R(N) TO R(N+0.5)

```

Figure 3a. Part I of Main Program for VLF Wave Interaction.

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9

15		CALL POSITN
	J(N+0.5)	
16		CALL CURRNT
	R(N+0.5) TO R(N+1)	
17		CALL POSITN
	RHO(N+1)	
18		CALL CHARGE
	E(N) TO E(N+1)	
19		CALL EFIELD
20	1000	CONTINUE
	STORE ALL DATA FOR CONSECUTIVE RUN	
21		CALL STORE
22		STOP
23		END

Figure 3b. Part II of Main Program of VLF Wave Interaction.

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Dispersion Check by EM2 Code

Parallel Propagation
($k \parallel B_0$)

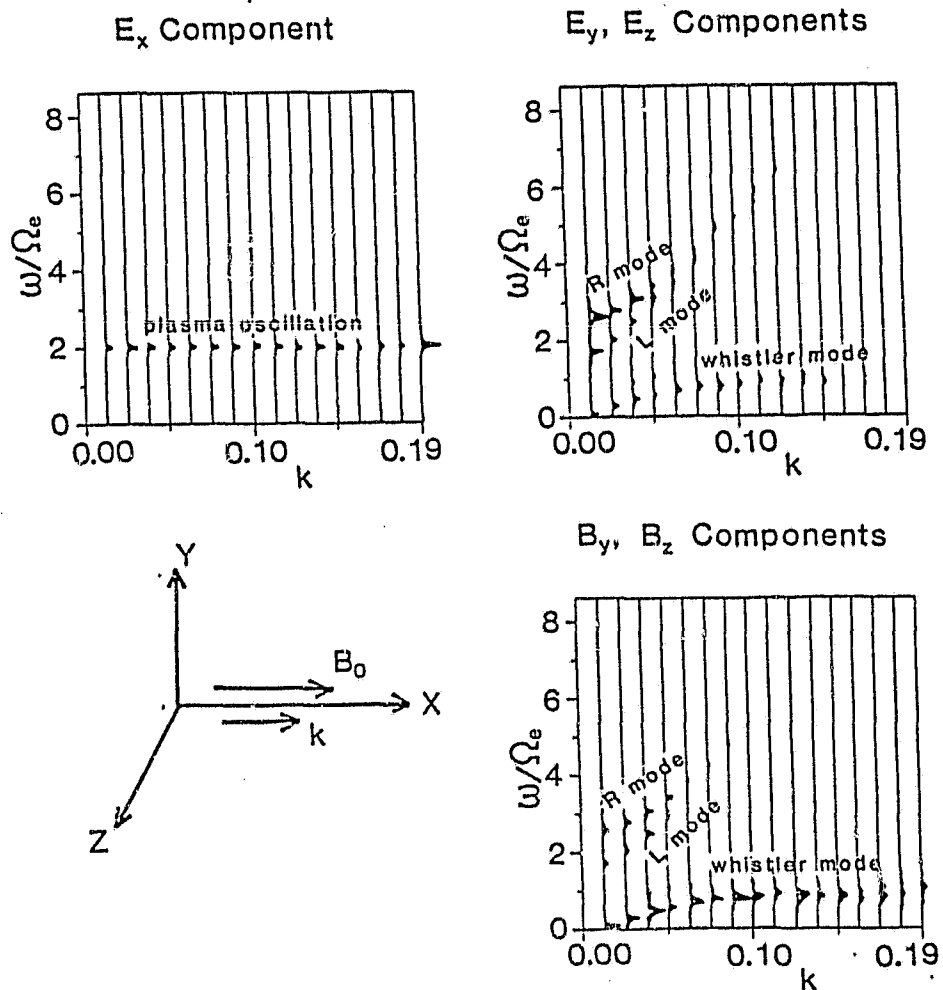
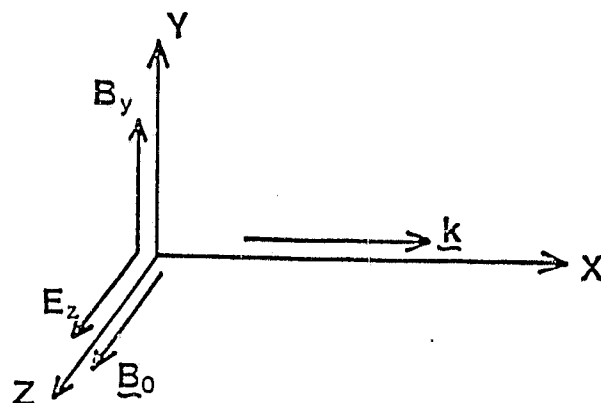


Figure 4-1. Results of dispersion characteristics tests:
Dispersion characteristics of waves propagating parallel
to the external magnetic field.

O-MODE



X-MODE

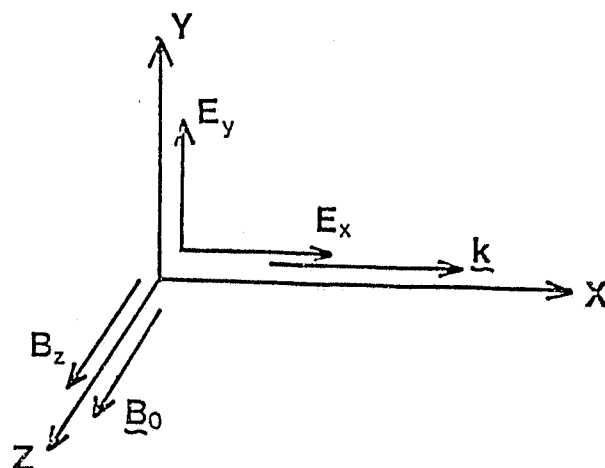


Figure 4-2. Results of dispersion characteristics tests: Magnetic and electric field vectors along with \underline{k} vector for perpendicularly propagating plasma wave modes (O- and X-modes).

Dispersion Relation by EM2 CODE
O MODE

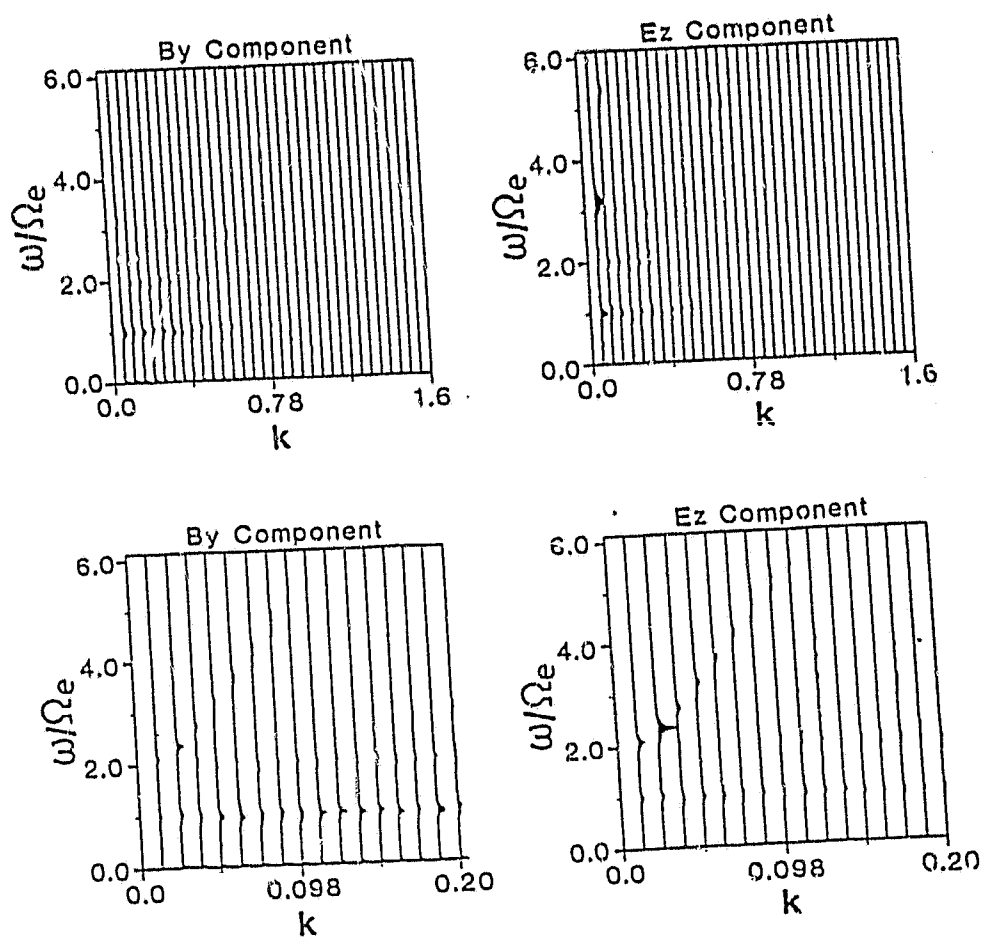


Figure 4-3. Results of dispersion characteristics tests:
Dispersion characteristics of O-mode waves.

Dispersion Relation by EM2 CODE
X MODE

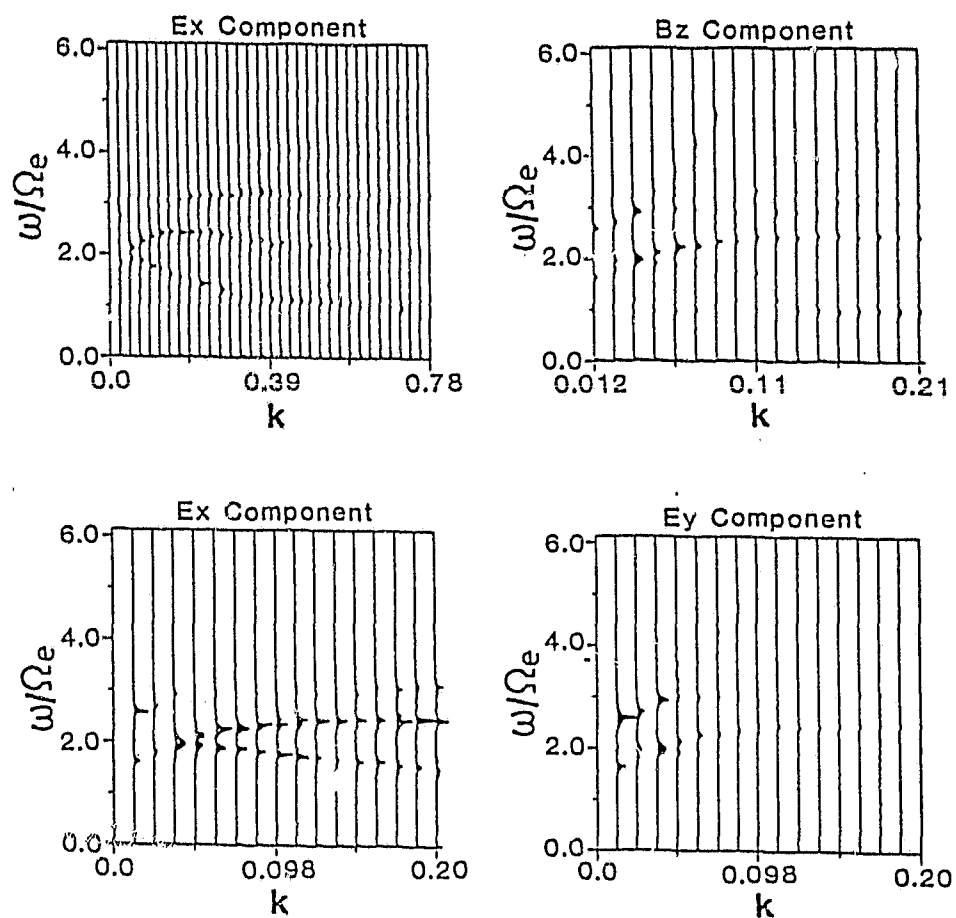


Figure 4-4. Results of dispersion characteristics tests:
Dispersion characteristics of X-mode waves.

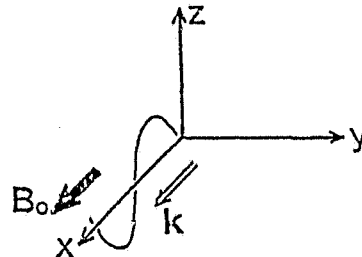
An interesting feature of Figure 4-3 is that the stimulation results show not only the ordinary electromagnetic mode, which is predicted by the linear cold plasma theory, but it also shows the existence of ordinary electromagnetic cyclotron harmonic waves at multiple frequencies of the cyclotron frequency ($\Omega_e = 1$). This mode was predicted from the kinetic linear theory by Russian physicists (e.g., Akhiezer et al. [1975]). Figure 4-4 shows the results for the X-mode analysis. In the B_z and E_y component, the fast and slow (in other words, Z-mode) extraordinary modes are clearly seen. In the B_z component, one can see a faint mode representing extraordinary electromagnetic cyclotron waves at the first and third multiples of the cyclotron frequency. In the E_x component, for which two figures are shown with small and large k regions, the electron Bernstein mode waves are clearly seen. All of these dispersion characteristics agree well with linear theory. Thus, as seen in Figure 4, the EM2 code reproduces all possible waves modes which are predicted by linear cold and kinetic theories.

The second check of the code was performed by propagation tests of three well-known modes. In Figure 5-1, the configuration of k vectors of those tested modes relative to the coordinate system and to the external magnetic field are shown. These three modes are a parallel propagating whistler wave, an electron plasma wave, and an obliquely propagating wave. The results of propagation tests of these waves are shown in Figures 5-2 to 5-4. All results show propagation characteristics which agree well with those predicted by the linear theory. In each figure, ω - k diagrams analyzed by FFTs are given with

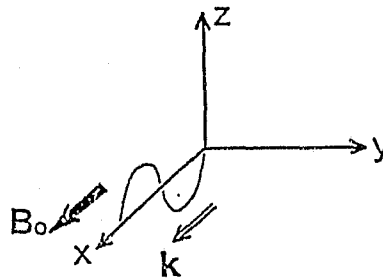
theoretical solid lines calculated by the linear theory.

Thus the development of the EM2 particle code has been completed and is now ready to be utilized for self-consistent simulation studies of nonlinear resonant interactions of electrons (and ions, if needed) with waves with k vector of arbitrary direction with respect to the external magnetic field, including a quantitative study of the ISEE wave and particle data.

ELECTRON PLASMA WAVE



WHISTLER WAVE
PARALLEL PROPAGATION



WHISTLER WAVE
OBLIQUE PROPAGATION

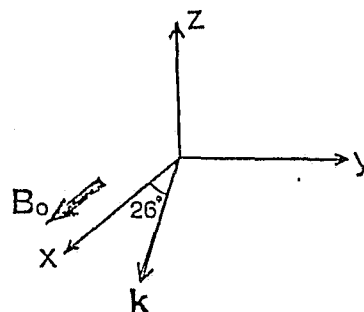


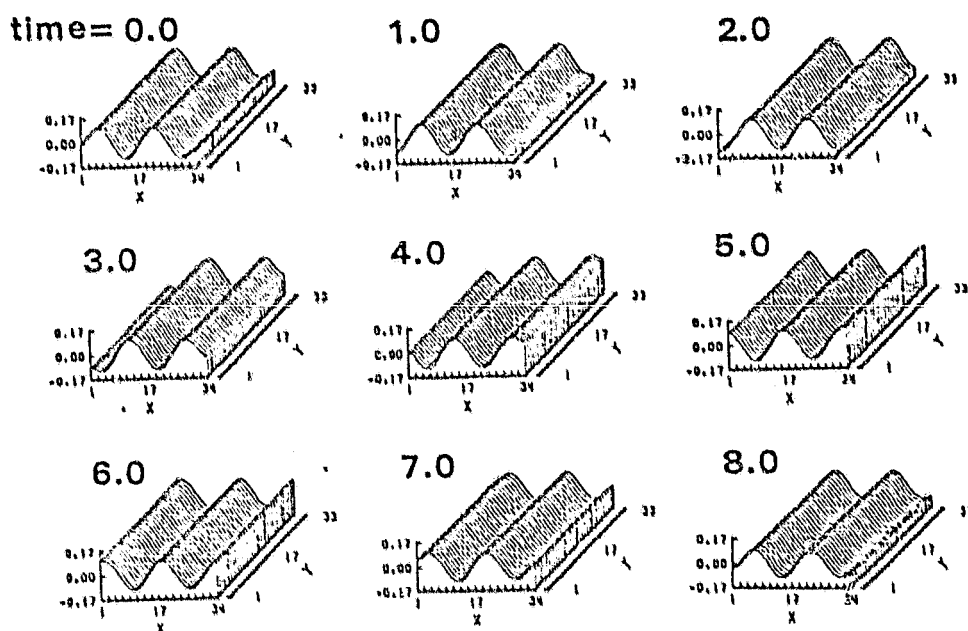
Figure 5-1. Results of test wave propagation: Configuration of k and B_0 vectors.

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WHISTLER WAVE

PARALLEL PROPAGATION TEST

(By Component)



ω - k
Diagram

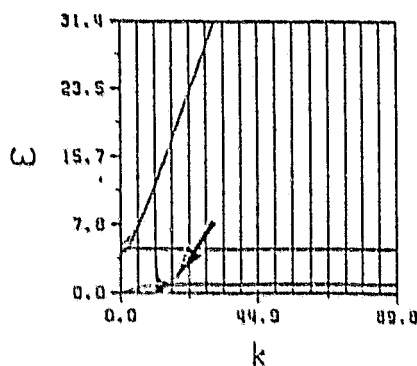
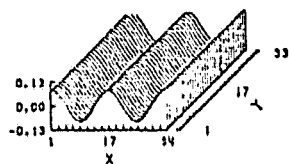


Figure 5-2. Results of test wave propagation: Propagation and ω - k diagram of parallel propagating whistler wave.

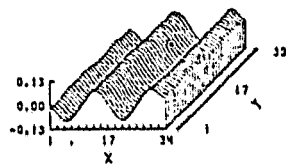
ELECTRON PLASMA WAVE PROPAGATION TEST

(Ex Component)

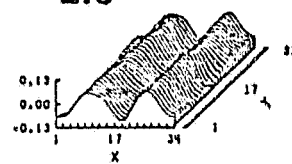
time=0.0



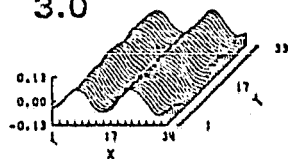
1.0



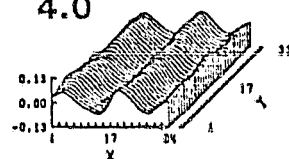
2.0



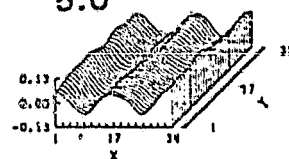
3.0



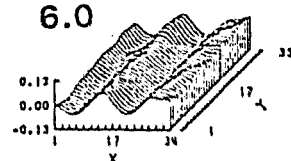
4.0



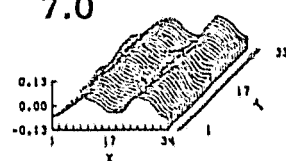
5.0



6.0



7.0



ω -K
Diagram

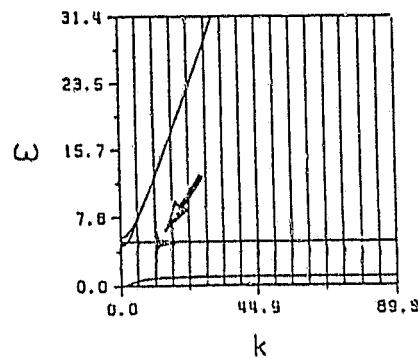
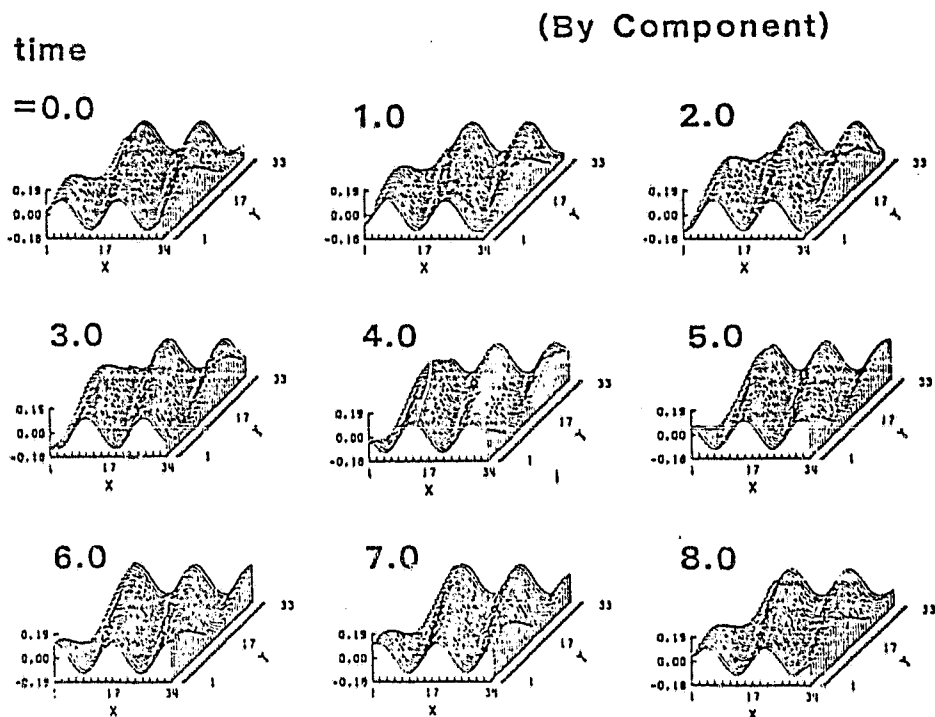


Figure 5-3. Results of test wave propagation: Propagation and ω -k diagram of electron plasma wave.

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WHISTLER WAVE OBLIQUE PROPAGATION TEST



ω -K Diagram

$\theta = 26^\circ$

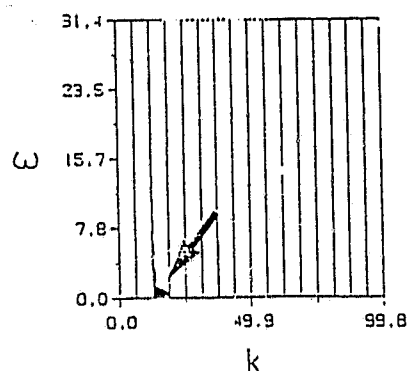


Figure 5-4. Results of test wave propagation: Propagation and ω -k diagram of obliquely propagating whistler wave.

References

Akhiezer, A. I., I. A. Akhiezer, R. V. Polovin, A. G. Sitenko, and K. N. Stepanov, *Plasma Electrodynamics*, Pergamon, New York, 1975.